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ABSTRACT

This research investigates the development of analogy, in particular, the study of the development of systematicity in analogy. Systematicity refers to the mapping of systems of mutually constraining relations, such as causal chains or chains of implication. A preference for systematic mappings is a central aspect of analogical processing in adults (Gentner, 1980, 1983). This research asks two questions: (1) does systematicity make analogical mapping easier; and (2) if so, when developmentally do children become able to utilize systematicity. Children aged 5-7 and 8-10 acted out stories with toy characters. Then they were asked to act out the same stories with new characters. Two variables were manipulated: systematicity, or the degree of explicit causal structure in the original stories, and the transparency of the object-mappings. Transparency was manipulated by varying the similarity between the original characters and the corresponding new characters; it was included in order to vary the difficulty of the transfer task. If children can utilize systematicity, then their transfer accuracy should be greater for systematic stories. The results show (1) as expected, transparency strongly influenced transfer accuracy: for both age groups, transfer accuracy dropped sharply as the object correspondences became less transparent; (2) for the older group, there was also a strong effect of systematicity and an interaction between the two variables. Given a systematic story, nine-year-olds could transfer it accurately regardless of the transparency of the object correspondences. (Author)

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Technical Report No. 358

SYSTEMATICITY AND SURFACE SIMILARITY IN THE DEVELOPMENT OF ANALOGY

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Abstract

This research investigates the development of analogy: in particular, we wish to study the development of systematicity in analogy. Systematicity refers to the mapping of systems of mutually constraining relations, such as causal chains or chains of implication. A preference for systematic mappings is a central aspect of analogical processing in adults (Gentner, 1980, 1983). This research asks two questions: (a) does systematicity make analogical mapping easier; and (b) if so, when developmentally do children become able to utilize systematicity.

Children aged 5-7 and 8-10 acted out stories with toy characters. Then they were asked to act out the same stories with new characters. Two variables were manipulated: systematicity, or the degree of explicit causal structure in the original stories, and the transparency of the object-mappings. Transparency was manipulated by varying the similarity between the original characters and the corresponding new characters; it was included in order to vary the difficulty of the transfer task. If children can utilize systematicity, then their transfer accuracy should be greater for systematic stories.

The results show (a) as expected, transparency strongly influenced transfer accuracy: for both age groups, transfer accuracy dropped sharply as the object correspondences became less transparent; (b) for the older group, there was also a strong effect of systematicity and an interaction between the two

variables. Given a systematic story, nine-year-olds could transfer it accurately regardless of the transparency of the object correspondences.

Systematicity and Surface Similarity in the Development of Analogy

Analogy is a central process in learning and discovery. For example, Sadi Carnot's great work on the principles of heat is pervaded by an analogy between heat and water: the 'fall' of heat from high temperature to low temperature is compared to the fall of water from high elevation to low elevation. Just as Carnot used this analogy to think through the mechanical action of heat, so a student learning water can use the same analogy to come to understand ideas like "The power released when heat flows between two bodies varies with the difference in temperature between them" (Buckley, 1979). But notice that to make this analogy useful the learner must focus on certain kinds of matches between the two domains (e.g., Clement, 1981, 1982; Collins & Gentner, in press; Forbus & Gentner, 1986; Kempton, in press; VanLehn & Brown, 1980). A learner who interpreted the analogy to mean that heat is wet or transparent like water might be worse off with the analogy than without it. The power of an analogy in learning is in the system of relations that can be mapped.

Focus on systems of mutually constraining relations is a central aspect of adult competence in processing analogy (Gentner, 1980, 1983). Adults not only have the ability to map a system of relations, but show a marked preference for such mappings (Gentner & Landers, 1985). This bias towards mapping

systems seems to reflect a tacit preference for coherence and mutual constraint in analogical mapping. This research asks two questions: (a) does the presence of systematic relations make analogical mapping easier; and (b) if so, when developmentally do children become able to utilize this systematicity.

The plan of the paper is as follows. We first give a brief review of the literature on analogical development. Then we present structure-mapping and the systematicity principle. Finally, we describe our research tracing the development of systematicity in analogy.

Development of Analogy

Since children are major consumers of education, it is important to know what they do with instructional and experiential analogies. Unfortunately there is a great deal of evidence suggesting that young children do not use analogies in the powerful systematic way that adults do. Experimental studies show a marked developmental change in children's fluency at interpreting metaphors. A four-year-old asked "Can a person be sweet?" answers literally: e.g., "Not unless he was made out of chocolate" (Asch & Nerlove, 1960). Similarly, young children are poor at matching sentences with metaphorically related pictures (Dent, 1984; Kogan, 1975) and at choosing appropriate metaphorical completions for sentences (Gardner, Kircher, Winner, & Perkins, 1975). Young children tend to produce and select attributional interpretations to nonliteral comparisons. This

pattern contrasts sharply with the adult preference for relational interpretations. For example, given the comparison "A cloud is like a sponge," five-year-olds produce interpretations like "Both are round and fluffy." Adults produce relational interpretations: e.g., "Both can hold water for some time and then later give it back" (Gentner, 1980; Gentner & Block, 1983; Gentner & Stuart, 1983). Further, adults rate analogical comparisons as more apt when they can find relational interpretations than when they can find only attributional interpretations. Children show no such preferences; they are equally happy with relational and attributional interpretations (Gentner, 1986; Gentner & Landers, 1985). These and many other experimental results seem to indicate that the ability to perform figurative comparisons develops gradually and late (Inhelder & Piaget, 1958).

However, it has been pointed out that a number of factors enter into the assessment of metaphoric and analogical ability (Gentner, 1977; Reynolds & Ortony, 1980; Vosniadou, 1985). Young children differ from older children in their command of the vocabulary, in their knowledge of the domains, and in their pragmatic understanding of when non-literal interpretations are permissible. This means that in many situations, especially with verbal interpretation tasks, there is danger of underestimating the young child's metaphorical ability and of conflating other

developmental trends with the development of true analogical ability.

In order to isolate development of analogy from other developmental trends, we must first delineate the essential processes that define analogy and metaphor. Then we can determine the course of development of analogy. In particular, we can ask when in development children become able to take advantage of systematicity.

Structure-mapping and Systematicity

The theoretical framework for this research is the structure-mapping theory of analogy (Gentner, 1980, 1982, 1983; Gentner & Gentner, 1983). This theory describes the set of implicit rules by which people interpret analogy and similarity. An analogy is a mapping of knowledge from one domain (the base) into another (the target), according to the following rules.[1] Objects in the base are placed in correspondence with objects in the target:

$$M: \quad b_i \dashrightarrow t_i$$

Predicates are mapped from the base to the target according to the following mapping rules:

(1) Attributes of objects are dropped:

e.g., [RED (b_i)] --> [RED (t_i)].

(2) Relations between objects in the base tend to be mapped across:

e.g., COLLIDE(b_i,b_j) --> COLLIDE(t_i,t_j)

(3) The particular relations mapped are determined by systematicity, as defined by the existence of higher-order constraining relations which can themselves be mapped:

e.g., CAUSE [PUSH(b_i, b_j), COLLIDE (b_j, b_k)] -->

CAUSE [PUSH(t_i, t_j), COLLIDE (t_j, t_k)]

Figure 1 shows an example analogy: the Rutherford analogy between the solar system and the hydrogen atom. Let us ask what this analogy conveys to the person hearing it for the first time. Assuming that the person has the prior knowledge about the solar system shown in the top network, the person must

- set up the object correspondences between the two domains: sun --> nucleus and planet --> electron.
- discard object attributes, such as YELLOW (sun).
- map base relations such as MORE MASSIVE THAN (sun, planet) to the corresponding objects in the target domain.
- observe systematicity: i.e., discard isolated relations, such as HOTTER THAN (sun, planet), and keep relations such as MORE MASSIVE THAN that are governed by higher-order constraining relations which can themselves be mapped. Here, the higher-order system is

  e.g., IMPLIES [MORE-MASSIVE-THAN (sun, planet), REVOLVE-AROUND (planet, sun)].

Insert Figure 1 about here.

Systematicity. Part of our understanding about analogy is that it conveys a system of connected knowledge, not a mere assortment of independent facts. The systematicity principle is included for formalize this tacit preference for coherence and deductive power in analogy. The systematicity principle states that a base predicate that belongs to a mappable system of mutually interconnecting relations is more likely to be imported into the target than is an isolated predicate. A system of relations refers to an interconnected predicate structure in which higher-order predicates enforce constraints among lower-order predicates.[2]

The systematicity principle requires a mappable relational chain. If the predicates, and especially the higher-order relations, of the base chain are not valid in the target, then another chain must be selected. Thus, a relational chain--such as a causal chain--in the base that matches a relational chain in the target constitutes good support for its members. Winston (1982) gives an insightful demonstration of the need for such importance-dominated matching.[3]

By promoting deep relational chains, the systematicity principle operates to promote predicates that participate in causal chains and in other constraint relations. It is an essentially syntactic mechanism that guarantees that the set of candidate mappings will be as interesting--in the sense that a

mutually interconnected system of predicates is interesting--as the knowledge base allows.

Ease of mapping. Our discussion so far has been couched in terms of the implicit standards for a good analogical mapping. Empirical studies have borne out the prediction that systematicity is one of the implicit rules for a good analogical mapping. Adults focus on shared systematic relational structure in interpreting analogy. They tend to include relations and omit attributes in their interpretations of analogy, and they judge analogies as more apt if they share systematic relational structure (Gentner, 1980; Gentner & Block, 1983; Gentner & Landers, 1985; Gentner & Stuart, 1983). From this we can conclude that systematicity is a desideratum in analogy; it is one of the criteria by which an interpretation is devised and by which the analogy itself is judged.

But we want to go beyond the prior evidence here to suggest that systematicity may also play an active role in guiding the on-line mapping process. We conjecture that the presence of higher-order constraints helps guide the mapping of lower-order relations and provides a check on the correctness of the mapping. An error made in mapping a particular relation from base to target is more likely to be detected quickly if there is a higher-order relation which relates that lower-order relation to other knowledge.

To see how this could work, imagine a learner who hears the Rutherford analogy, "The atom is like the solar system," for the first time. Let us assume that the learner knows something about the solar system and little or nothing about the structure of the atom, and must map information from his model of the solar system. We contrast the case in which the learner has a systematic representation of the solar system with that in which he does not. In each case, we will assume the learner makes one mistake in mapping predicates from base to target. Then we will contrast the two cases--the systematic knowledge case and the nonsystematic knowledge case--to show how systematic knowledge enables the learner to repair mapping errors.

Figure 2 shows two representations of the solar system/atom analogy: a systematic representation (Figure 2a) and a nonsystematic representation (Figure 2b).

Insert Figure 2 about here.

Suppose that the learner momentarily switches the objects when mapping the MORE MASSIVE THAN predicate and ends up with

MORE MASSIVE THAN (electron, nucleus).

At this point the learner is in danger of ending with a garbled and inaccurate notion of the structure of the atom. Now let us take the two cases in turn.

Systematic knowledge case. For the learner who has a systematic model of the base domain, there is a higher-order causal relation that can be mapped from base to target. This gives the learner a way of spotting the error. For at this point he has the following derived propositions in the target:

1. MORE MASSIVE THAN (electron, nucleus)
2. REVOLVE AROUND (electron, nucleus) (We assume both learners have mapped this lower-order relation correctly.)
3. CAUSE [MORE MASSIVE THAN (electron, nucleus), REVOLVE AROUND (electron, nucleus)]

The last assertion is the causal chain that the learner derives by plugging in his (partly erroneous) lower-order mappings to the higher-order CAUSE relation. This chain can be compared to the similar causal statement that the learner knows from the base domain:

- CAUSE [MORE MASSIVE THAN (sun, planet), REVOLVE AROUND (planet, sun)]

Comparing these two chains, the learner can see an inconsistency. In the base domain, the less massive object revolves; in the target, the more massive object revolves. One way to resolve the inconsistency is to recheck the object mappings, giving the learner an opportunity to correct his error. Thus systematic knowledge of the base domain should allow the learner to detect and repair an incorrect local mapping.

Nonsystematic knowledge case. The learner's derived representation of the target domain has only the two lower-order relations:

1. MORE MASSIVE THAN (electron, nucleus)
2. REVOLVE AROUND (electron, nucleus)

There is nothing to alert him to an error in mapping these relations. Without systematic structure to map from the base domain, the learner simply has a disconnected set of low-order predicates. Thus he is unlikely to notice and repair a mapping error.

Based on this reasoning, we conjecture that the presence of systematic relational structure should provide an on-line check on the correctness of the individual lower-order predicate mappings. Thus, systematicity should increase the transfer accuracy of an analogical mapping. Another factor that should be important during the on-line mapping process is the transparency of the object-correspondences. Transparency is defined as the ease of determining the object correspondences and predicate mappings for an analogy or similarity match. Transparency is high when surface similarity correlates well with structural similarity. There is evidence that transfer accuracy is greater for high-transparency analogies (Reed, 1985; Ross, 1986). We predict that transparency will have a strong effect on transfer accuracy. To the degree that it is easy to determine how the objects in the base correspond with the objects in the target,

the transfer of predicate structure from base to target should be easier.

This line of reasoning leads us to three predictions concerning analogical mapping:

1. Transparent object-correspondences promote accurate mapping.
2. Systematic knowledge of the base domain leads to more accurate analogical mapping.
3. The effect of systematicity will be stronger the more difficult (the less transparent) the analogical mapping.

The Development of Systematicity

In this research, we investigated the development of systematicity in analogical mapping. We wished to discover when children become able to benefit from the presence of a system of mutually constraining relations in carrying out an analogy. To do this, we used a technique we called cross-mapping to vary the transparency of a set of analogical mappings. Then we gave children either systematic or nonsystematic base scenarios to map, as described below. The question was whether the degree of systematicity would affect children's ability to perform analogical transfer. If children's accuracy is improved by the presence of systematically connected knowledge structures, this is evidence that they can appreciate systematicity, whether or not they are able to articulate this appreciation explicitly. Our method was designed to avoid the confoundings inherent in

requiring a verbal interpretation. The children were simply asked to act out stories using toy dolls and animals. The analogical step was that the children had to transfer a story plot from one set of characters to another. An important aspect of the methodology is that we do not require our subjects to articulate the higher-order information. Children are compared only in their accuracy at acting out the low-order event predicates, which are identical in systematic and nonsystematic stories. Thus any developmental differences in the effects of systematicity here are likely to reflect true cognitive differences, and not merely differences in facility with language.

In order to fully test the effects of systematicity, we wanted to include a wide range of mapping difficulty. This brings us to the second theoretical question addressed in the study: the effects of varying the transparency of the object correspondence between base and target. To achieve this variation, we varied the surface similarity between the characters and the test characters. There were three levels of transparency: (a) high transparency--test characters look highly similar to corresponding original characters; (b) moderate transparency--test characters look quite different from corresponding original characters; and (c) low transparency--test characters look similar to non-corresponding original characters (the cross-mapped case). The cross-mapped case is predicted to

be very difficult, because the object similarities between base and target are deliberately misleading. A given test character looks like one of the original characters, but plays a different role in the story. An example will help make the three transparency conditions clear. Suppose that in the original story the hero was a chipmunk, the hero's friend was a robin and the villain was a horse. Then the roles in the three kinds of mapping conditions might be

	ORIGINAL	HIGH	MEDIUM	LOW
HERO	chipmunk	squirrel	elephant	zebra
FRIEND	robin	bluebird	shark	squirrel
VILLAIN	horse	zebra	cricket	bluebird

The design included age and systematicity as between-subjects variables and transparency as a within-subjects variable. We predicted that children's accuracy in enacting the second story would be greatest in the high-transparency mapping condition and lowest in the low-transparency cross-mapped condition, where the natural object mappings had to be resisted. Besides this prediction, there were three questions of interest:

- whether transfer accuracy would be higher for systematic stories than for nonsystematic stories
- if so, when such systematicity effects would show up developmentally
- whether systematicity would interact with mapping difficulty.

This last question is particularly interesting from our theoretical perspective. For if the presence of systematic higher-order relations helps the child preserve the relational structure she is trying to map, then the more difficult the mapping the greater the potential benefit of systematicity.

Method

Subjects

The subjects were 72 children, 36 four- to six-year-olds and 36 eight- to ten-year-olds, recruited from schools and preschools in Cambridge, Massachusetts. They were randomly assigned to either the systematic or the nonsystematic condition. Approximately equal numbers of males and females were included within each of the two experimental conditions, within each age group.

Materials

Stories. Nine short stories were constructed, each involving three characters and depicting a series of actions which led to a final outcome. There were two versions of each story: systematic and nonsystematic. The structure of the stories was as follows: (a) an introductory section, which introduced the characters; (b) an event sequence, with an outcome; (c) a moral (in systematic versions only). For each story, the event sequence was a set of 10 to 15 sentences depicting a series of events and an outcome. This section was identical in the systematic and nonsystematic story types. The

story types differed only in their introductory sections and in whether they contained a moral. Table 1 shows sample stories.

Insert Table 1 about here.

For both kinds of stories, the introductory section was one or two sentences long and contained (a) some descriptive information about the protagonist (e.g., "There once was a very handsome chipmunk.") and (b) some relation between the protagonist and one of the other two characters (e.g., "The chipmunk was friends with the cow."). The relation between the characters was the same in the systematic and nonsystematic story types. However, the information about the protagonist differed between the two story types. In the systematic stories, the description of the protagonist concerned a relevant habit or relational trait (e.g., "The chipmunk was very jealous"). In the nonsystematic stories the description attributed a neutral trait (e.g., "The chipmunk was very good-looking."). For both systematic and nonsystematic stories, the introductory sections were designed to define the roles of the characters. This meant that, to set up a transfer test, we could simply read the child the introduction with the new character assignments; this determined the rest of the story.

Aside from the difference in the introduction, the systematic stories differed from the nonsystematic stories in

possessing a moral: a final sentence that expressed a moral and linked the protagonist's initial character trait to the story outcome (e.g., "The chipmunk realized that he shouldn't be so jealous, because it is better to have more friends." No moral was added to the nonsystematic stories. The systematic stories, with a mean word length of 200 words, were somewhat longer than the nonsystematic stories (with a mean word length of 170 words), chiefly because of the presence of the moral. Half the children received systematic stories; the other half, nonsystematic stories.

Story-telling stimuli. Sixty-three toy dolls and animals were used to depict the characters. Of these, there were 27 pairs of animals that were independently judged by three judges to be 'similar-looking,' and nine animals that were judged to be 'different-looking' from one another and from any of the paired animals. A small number of props were used to aid in the story-telling. For each story, one or two rectangular, colored felt pieces were used to mark key locations, such as a house or road. For some stories, one or two additional toys, such as a wagon or plastic food, were used as props.

Mapping conditions. For each target story, three further stories were constructed using different sets of characters. These three story types reflected three mapping conditions corresponding to high, medium or low transparency:

- S/S: Similar Characters / Similar Roles (High Transparency)
- D: Different Characters / Similar Roles (Medium Transparency)
- S/D: Similar Characters / Different Roles (Low Transparency)

In the S/S condition, the test characters looked like the characters in the original story, and they played the same role as their counterparts in the original story. In the D condition, the test characters bore no resemblance to any of the characters in the original story. In the S/D condition, the test characters resembled those in the original story, but were given different roles from their look-alike counterparts in the original story. This was predicted to be the most difficult mapping condition. Table 2 shows the object mappings for all nine stories.

Insert Table 2 about here.

The mapping condition could have been varied by giving all children the same base story and then varying the target story. As Table 2 shows, we decided instead to vary the original base story that the children heard. Thus, a child in the S/S condition and a child in the S/D condition would receive different original stories, but the same target story. This was done in order to achieve strict comparability on the test phase.

Since the child can receive help or extra practice when necessary in acting out the original stories, any small differences in the ease of comprehension of the original stories are less likely to affect the overall results than would differences in the test stories. Thus the base stories varied according to systematicity (systematic or nonsystematic) and mapping condition (S/S, D, or S/D), for a total of six kinds of base stories (see Table 2).

All children received three stories in each of the three mapping conditions, for a total of nine stories. The assignment of stories to mapping condition was counterbalanced across groups of children. The mapping conditions (S/S, D and S/D) were presented in three different orders, according to a Latin square design. There were two orderings--one the reverse of the other--for the stories themselves. Thus, children were divided into 12 groups according to their Systematicity Condition, Mapping Order and Story Order. However, the essential experimental variables were Age (2 levels, between), Systematicity (2 levels, between) and Mapping Condition (3 levels, within).

Procedure

Children were read aloud the stories and asked to act them out with toy animals. Once they had acted out a story, they were asked to act out the same story again, only with new characters. A practice session using a four-line story about two characters was used to acquaint subjects with their task. During the practice session, children were encouraged to tell the story and

speak the dialogue. The experimenter demonstrated the two-fold task for the child if necessary. The experiment began once a child demonstrated the ability to perform the transfer task successfully without help. The experimental procedure was the same for each story and was divided into two parts: the Story Phase and the Test Phase.

Story phase. The experimenter began each story by introducing the three story characters (e.g., 'Here is the moose.'). The experimenter made sure that the child could correctly name the toys before proceeding. With the story characters in view, the child was then instructed to listen carefully to the story. After the experimenter finished reading the story aloud, props, including location markers, were introduced: e.g., the 'wheelbarrow' or the 'lake.' Some individual variation in the use of props was allowed, as long as the child used each prop consistently. The child then acted out the story, using the characters and props. If the child made omissions or errors, the experimenter corrected them and asked the child to again act out the story. Once the child demonstrated the ability to act out the original story correctly without help, the Test Phase began.

Test phase. The experimenter then asked the subject to act out the same story again, but with three new characters. The three original story characters were removed from view and the new test characters were introduced: e.g., 'This is the

squirrel.' Location markers, such as the 'lake,' were left in the same position, and props were gathered and set before the subject to use. The child was then instructed to listen carefully to the beginning of the story with the names of the new characters. The experimenter read aloud the introductory section and repeated it if desired. Then the child was told to act out the rest of the story.

The stories were designed so that the introductory section set the roles of the characters in such a way as to determine the rest of the story for a child who had performed the character-mapping correctly. During the test phase, the experimenter did not provide the subject with any information regarding mapping assignments, omissions, or errors. However, the experimenter could give neutral prompts, such as "What happened next?" or "Who is doing that?" In addition, the experimenter would repeat the correct name(s) of the character(s) or the introductory section on request.

The Story and Test Phases were carried out in the same way for each story. Children were given three stories in a test session, with a two-minute distractor task of coloring or putting together a puzzle between stories. Each child participated in three test sessions, spaced at least a day apart.

Scoring. For each story, the sentences were grouped into six core propositions representing the major events and the outcome. The moral in the systematic stories constituted a

seventh proposition that was scored separately. In scoring, propositions were treated as wholes. If an error was committed with respect to any one character or action contained in a proposition, the proposition was considered incorrect. Thus, for each subject there were six possible correct propositions per story. The same six propositions were scored for systematic and nonsystematic stories.

Three scoring procedures were used: Strict, Lenient and Key Sentence scoring. However, since all gave the same results, we describe only the strict scoring procedure. In the strict scoring procedure, a proposition was scored as correct if the child either verbally or nonverbally depicted each of its events with the correct assignment of actors. Two types of errors were scored: omissions and incorrect answers. A proposition was scored as an omission if the subject verbally omitted any action or character contained in that proposition AND failed to adequately demonstrate the inclusion of the action or character through nonverbal actions. A proposition was scored as incorrect if any character or action contained in that proposition was incorrectly identified AND the subject failed to correctly identify the character or action in question through nonverbal actions.

Results

The results are shown in Figure 3. These results show:

1. as predicted, object-mapping transparency had strong effects on transfer accuracy for both age groups.
2. systematicity benefited only the older group.
3. the benefits of systematicity were strongest in the most difficult mapping condition.

Insert Figure 3 about here.

A 2 x 2 x 3 mixed-measures analysis of variance of Age (Between) X Systematicity (Between) X Mapping Condition (Within) showed main effects of Age [$F(1,68) = 14.93$, $p < .001$], Systematicity [$F(1,68) = 6.28$, $p < .05$], and Mapping Condition [$F(2,136) = 29.01$, $p < .000001$]. There was also the predicted interaction between Systematicity and Mapping Condition [$F(2, 136) = 3.89$, $p < .05$].

Although both Mapping Condition and Systematicity show main effects, their developmental patterns differ. Mapping Condition shows strong effects for both age groups. As predicted, the children performed best with the easy S/S mapping, intermediate with the D mapping, and worst with the misleading S/D mapping. Planned comparisons confirmed that Mapping Condition had significant effects on both age groups.

In contrast, Systematicity showed significant effects only in the older group. For the older children, performance was significantly better on systematic stories [$t(34) = 2.48$, $p < .01$]. This was not true for the younger children; they derived no significant advantage from systematic plot structure [$t(34) = 1.08$, NS].[4]

The last prediction was that Systematicity should have its greatest effects on the most difficult mappings (since these are the mappings in which the children cannot rely on object similarity to perform the transfer). This prediction was confirmed by the Systematicity X Mapping Condition interaction noted above. More to the point, planned comparisons within the older group (the only group affected by Systematicity) confirmed that Systematicity was significant only in the S/D condition. Thus the presence of systematic relational structure created a significant improvement only in the most difficult mapping condition.

It might be wondered whether the systematicity advantage in transfer was simply a memory phenomenon. We know that the degree of structure and organization plays a role in how well material can be remembered (e.g., Bower & Clark, 1969; Bransford & Johnson, 1972; Mandler, 1967); perhaps the eight-year-olds were simply better able to remember the systematic stories during the mapping task. Then the systematicity advantage would tell us nothing about mapping, but only reaffirm the superiority of

organized structures in memory. There are three arguments against the memory interpretation of the data. First, the children were uniformly able to perform the original story enactments--i.e., the enactments using the initial set of characters. Since this, too, was a memory task, any difference in memory for the original stories should have shown up here. Recall that the transfer enactment is done immediately after the initial story enactment, so there should be little opportunity for forgetting. Second, the interaction between systematicity and mapping condition discussed in the preceding paragraph shows that the effects of systematicity were specific, rather than an across-the-board advantage. Third, and most important, all children regardless of systematicity condition performed nearly perfectly on the high-transparency transfer task. When the transfer mappings were easy, children could demonstrate nearly perfect memory for the original story in both the systematic and nonsystematic condition. Thus we conclude that the differences in transfer accuracy are not due to differential forgetting but arise during the mapping process itself.

These results suggest that systematicity indeed plays a role in the mapping process: that children, at least by the age of eight, can use higher-order constraints to help keep the lower-order predicates straight. We found informal support for this claim in the self-corrections that the older children occasionally made. A child would begin to make an error, acting

out an event with the wrong character, and then stop herself with a remark like "No, wait, it's the greedy one who got stuck in the well, because he ate too much." These children, then, used higher-order relations to check the correctness of lower-order predicates during the mapping.

Discussion

In this research, we found effects of both systematicity and transparency on the accuracy of children's analogical mappings. These results have implications both for theories of analogical processing and for accounts of the development of analogy and metaphor. We begin by discussing the implications for theories of analogy.

Systematicity in Analogical Mapping

The principle of systematicity is becoming increasingly prominent in computational approaches to analogy (e.g., Burstein, 1983; Carbonell, 1983; Gentner, 1980, 1982, 1983; Gentner & Gentner, 1983; Rumelhart & Norman, 1981; Winston, 1980, 1982). Although accounts vary in detail, it is generally supposed that the presence of some kind of common higher-order constraining structure is an important determinant of the utility of an analogy for learning and transfer. However, there has been little evidence about how systematicity enters into the analogical process. Is it simply a passive desideratum, which the learner checks after interpreting an analogy to decide which interpretation to choose and to determine how good the analogy

is? This limited view of systematicity is contradicted by the present research. Our results show that systematicity enters into the mapping process itself.

In this work we go beyond structure-mapping as a competence theory--a theory of how people think an analogy should be mapped--and consider its implications as a performance theory. We ask what makes an analogy easy to process; and in particular whether systematicity plays a role in making analogical mapping easier. According to structure-mapping theory, once the base and target domains have been accessed, the mapping process involves setting up object-correspondences and carrying across predicates. This suggests that at least two factors should enter into the difficulty of the mapping process. The first is the transparency of the object-correspondences: the more similar the corresponding objects in base and target, the easier it should be to keep the mapping straight, which here was manipulated by varying the similarity among corresponding objects of base and target. The second factor is the sturdiness of the predicate structure that is to be mapped from base to target. This is where systematicity enters in. The presence of constraining higher-order relations that govern the lower-order predicates both guides the on-line mapping of lower-order predicates and provides the learner with checks on the correctness of the mapping. Indeed, we saw children correct their enactments when

they remembered higher-order information that predicted a different event.

The theory predicts that both systematicity and transparency should facilitate analogical mapping.[5] Both these claims were verified for the eight-year-olds. We believe the same pattern of results will hold for adults. Preliminary results using an adult version of the same paradigm indicate that adults take longer to retell the story in the most difficult mapping condition--the cross-mapping case with a nonsystematic base story--than they do in the more natural conditions.

Developmental Implications and Further Questions

Two developmental questions were posed here:

1. Are there developmental differences in the effects of difficult object correspondences in analogical mapping?
2. Do children change in their ability to profit from systematic relational structure in dealing with those difficult correspondences?

One useful aspect of this methodology for studying development is that it allows an indirect measure of the child's ability to use systematicity. Research on development of metaphor has shown repeatedly that children do not articulate their interpretation of metaphors in the same manner as adults (Gardner, Kircher, Winner & Perkins, 1975; Gentner & Stuart, 1983; Reynolds & Ortony, 1980; Vosniadou & Ortony, 1983; Winner, Rosenstiel & Gardner, 1976). However, we cannot therefore infer that children

are intellectually unable to perform metaphorical and analogical transfer (cf. Brown & Campione, 1985; Carey, 1984; Winner, Engel & Gardner, 1980). There is some evidence that children can perform analogical mappings without necessarily being able to articulate all the predicates that they are mapping (Crisafi & Brown, 1983; Gardner, 1974; Gentner, 1977; Holyoak, Juin, & Billman, in press); see Vosniadou (1985) for a review of this issue. In the present methodology, children simply acted out stories with a new set of characters. Thus, although they were not required to verbalize the relational structure that they were carrying across, their ability to make the transfer was clear from the accuracy of their reenactment. Given that the child can act out the original story (which was in all cases true), we found:

1. children of both ages were affected by the transparency of the object mappings.
2. systematicity benefited the older children.
3. systematicity had its greatest effect when the object mappings were most difficult.

The transparency of the object-mapping affects both younger and older children. Object similarity between base and target may well be important in determining the ease of analogical processing at all levels of development. The work of Ross (1984, 1986) and Reed (1985) suggests that even adults are greatly influenced by the degree of surface similarity between potential

analogs in learning and problem-solving tasks. In developmental research on transfer tasks, the reliance of young children on surface information is well-established (Keil & Batterman, 1984; Kemler, 1983; Shepp, 1978; Smith & Kemler, 1977). Research by DeLoache (1984) provides a particularly striking demonstration of young children's reliance on surface similarity in transferring knowledge. She tested children of 2 1/2 to 3 years of age in a transfer-search task: an object is hidden in one space--for example, a room--and the child must find a like object in a similar space--for example, another room or a smaller scale model of the original room. She finds that the children's performance is extremely sensitive to surface similarity between the original space and the search space. Our results are compatible with DeLoache's findings in suggesting that transparency may be developmentally among the earliest determinants of ease of analogical mapping.

Systematicity, on the other hand, may make a somewhat later developmental appearance. In our research, systematicity effects were clearly present among the eight-year-olds, but not among the younger children. However, our conclusions here must be tentative; it is possible that with more sensitive methodology or different materials we could find systematicity effects earlier in development. Moreover, if indeed young children are deficient in their ability to benefit from systematicity, there are at least two different extreme interpretations, one based on

developmental increases in intellectual competence and other based on acquisition of knowledge. The competence interpretation is that younger children lack the processing ability to map whole systems of relations. Their failure to use systematicity reflects a developmental limitation in their basic competence. The knowledge-based interpretation is that the younger children had insufficient familiarity with the higher-order relations used here. Thus even if they were intellectually able to use systematicity in mapping, they were not in position to demonstrate that ability. By this account, the difference between younger and older children found here is a novice-expert shift in the sense of Chi, Glaser and Reese (1982) or Larkin (1983). From what we know so far, either account or a combination could be correct.

To recapitulate, in this research we found that both younger and older children did better when the object correspondences were highly transparent. Only the older children benefited by systematicity. In view of the centrality of systematicity in analogical transfer, this developmental trend is important whether it is a knowledge-based or a competence-based phenomenon. The results of this study help us to delineate the subcomponents of the mapping process and to chart their developmental course.

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Footnotes

[1]Besides analogy, other kinds of similarity can be characterized by the distribution of relational and attributional predicates that are mapped. In analogy, only relational predicates are mapped. In literal similarity, both relational predicates and object-attributes are mapped. In mere-appearance matches, it is chiefly object-attributes that are mapped.

[2]The order of a relation is determined by the order of its arguments. A first-order relation is one that takes objects as its arguments. A second-order relation has at least one first-order relation among its arguments. An nth order relation has at least one (n - 1)th order argument.

[3]A relational chain can also provide support--particularly in cases where little or nothing is known about the target domain--if it merely generates no contradictions in the target.

[4]It should be noted that there was no significant Age X Systematicity interaction in the overall analysis of variance. Therefore it is possible that systematicity benefited both groups, but that only in the older group did the effects reach significance.

[5]Note that, although both systematicity and transparency are postulated to make analogical mapping easier, only systematicity enters into the perceived soundness of an analogy. Indeed, if the object similarity becomes too high, the comparison becomes a literal similarity match instead of an analogy.

Table 1

Sample Story, in Systematic and Nonsystematic Versions

(Systematic Version Includes Indented Material)

> Setting a: There once was a very jealous cat who was friends with a walrus. The cat often said to the walrus, "Don't ever play with anyone else but me."

One day the cat went away on a trip and the walrus had no one to play with. But then a seagull came to visit the walrus. He brought a wagon along and said, "Would you like to play with me and my wagon?" The walrus said, "Yes." The seagull and the walrus had a great time pulling each other around in the seagull's wagon.

When the cat came back and found the walrus playing with someone else he got very angry. He shouted, "I'll never play with you again!"

The cat was so angry that he jumped into the seagull's wagon. But the wagon began to roll faster down a steep hill. The cat was very scared.

The seagull jumped up and chased after the wagon so the cat wouldn't crash. The seagull stopped the runaway wagon and saved the cat's life.

> Moral b: In the end, the cat realized that being jealous only got him into trouble. It is better to have two friends instead of one.

a. Setting, Nonsystematic Version: There once was a very strong cat who was friends with a walrus.

b. Moral is omitted in nonsystematic version.

Table 2

Characters Used in the Stories, Showing the Three Mapping Conditions for each Story

Story	Test	S/S	D/S	S/D
1	seal	walrus	lion	cat
	penguin	seagull	giraffe	walrus
	dog	cat	camel	seagull
2	goose	swan	giraffe	raccoon
	panda	raccoon	camel	monkey
	chimp	monkey	lion	swan
3	hare	rabbit	camel	bear
	beaver	bear	giraffe	porcupine
	mole	porcupine	lion	rabbit
4	bull	cow	shark	cricket
	mule	camel	elephant	cow
	ant	cricket	lion	camel
5	moose	elk	shark	medicine man
	hog	pig	elephant	elk
	warrior	medicine man	lion	pig
6	dragon	dinosaur	lion	unicorn
	horse	unicorn	shark	eel
	snake	eel	elephant	dinosaur
7	hunter	cowboy	ostrich	fly
	pony	zebra	turtle	cowboy
	spider	fly	giraffe	zebra
8	gorilla	orangutan	giraffe	lizard
	steer	buffalo	turtle	orangutan
	alligator	lizard	ostrich	buffalo
9	eagle	vulture	turtle	bobcat
	hippo	rhino	giraffe	vulture
	tiger	bobcat	ostrich	rhino

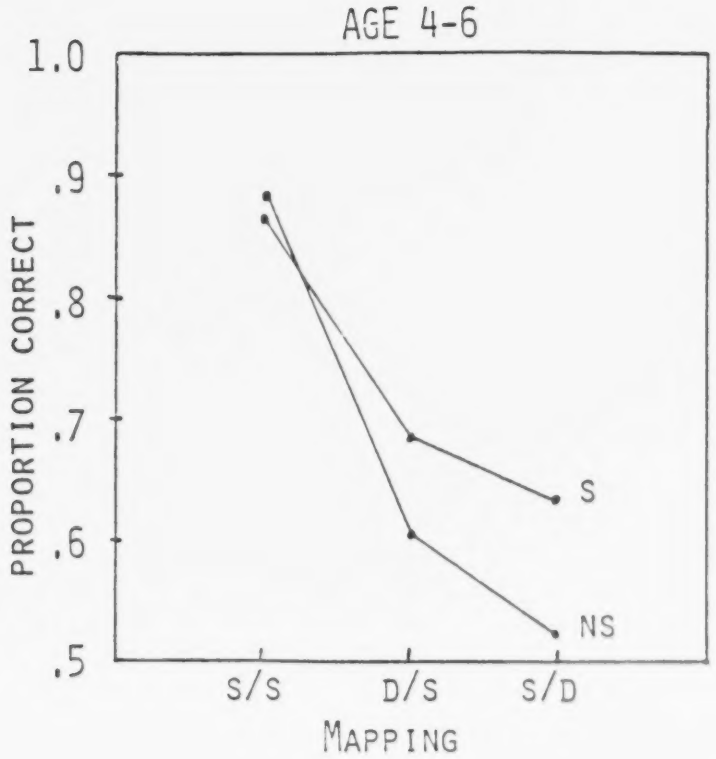
Figure Captions

Figure 1. Partial depiction of the analogy between solar system and hydrogen atom, showing a person's presumed initial knowledge of the solar system and the mapping of that knowledge to the atom.

Figure 2. More detailed depictions of a person's representations of the solar system.

- a. Systematic representation
- b. Nonsystematic representation

Figure 3. Results: Proportion of statements in the target stories correctly enacted under different conditions for four-to-six-year-olds (top graph) and eight-to-ten-year-olds (bottom graph).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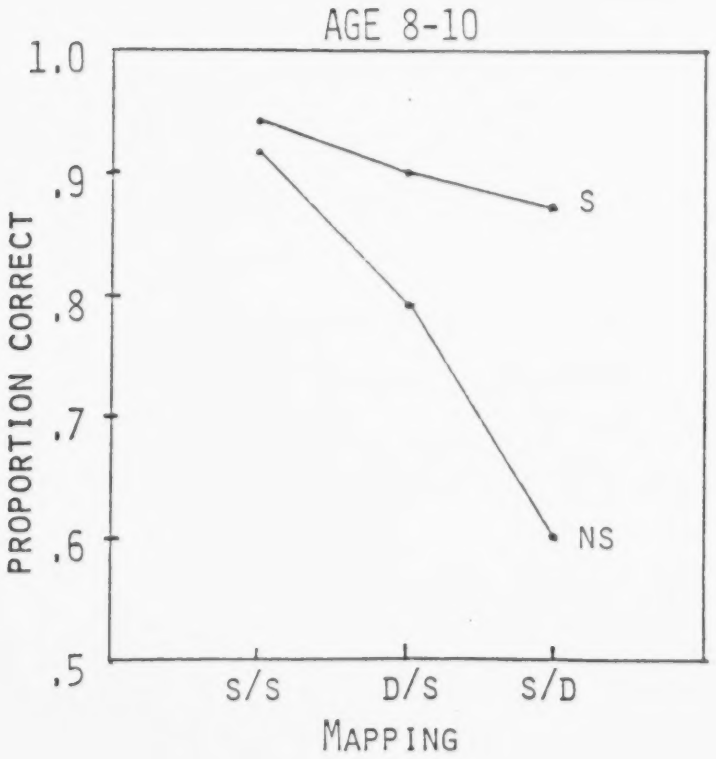
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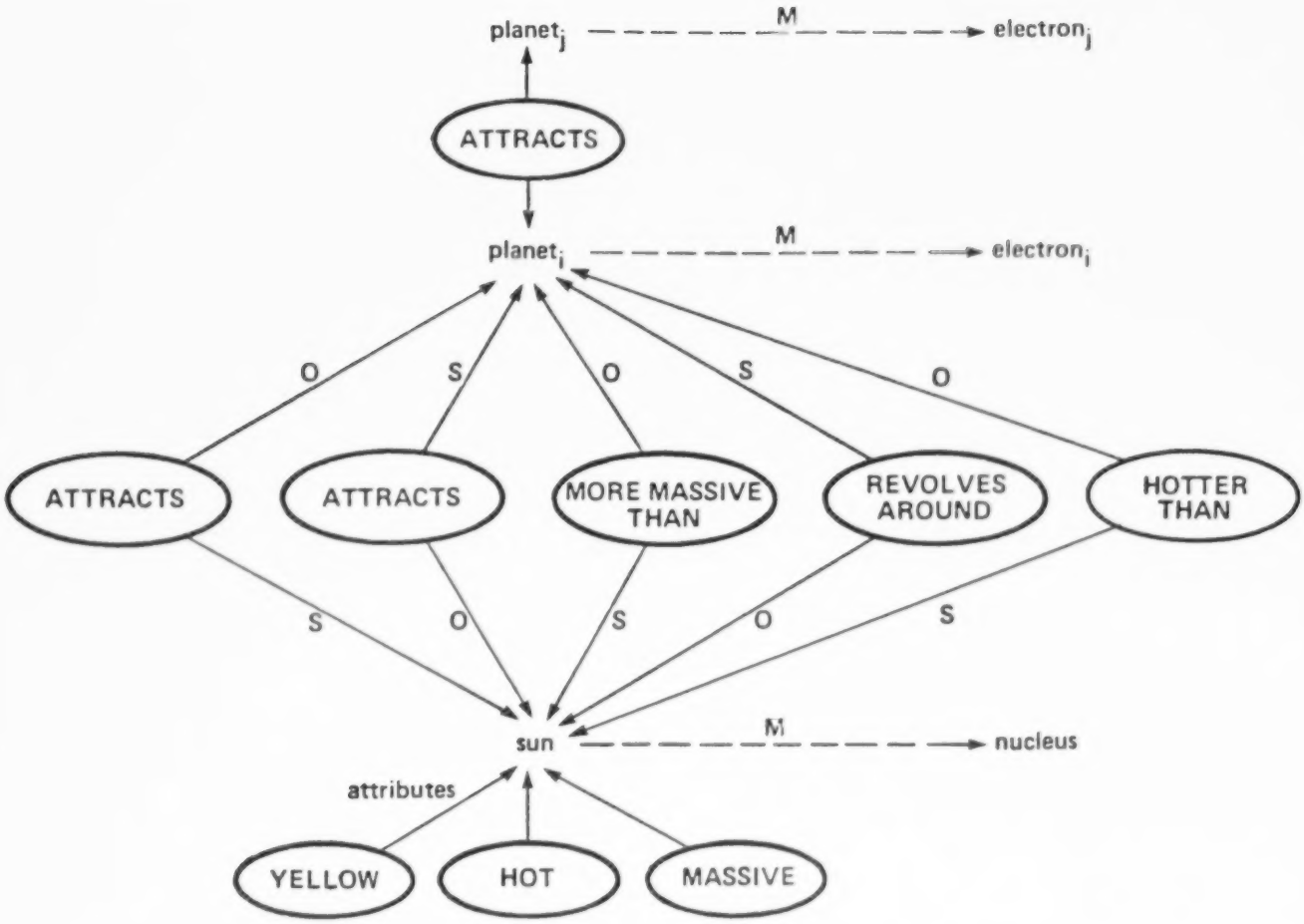
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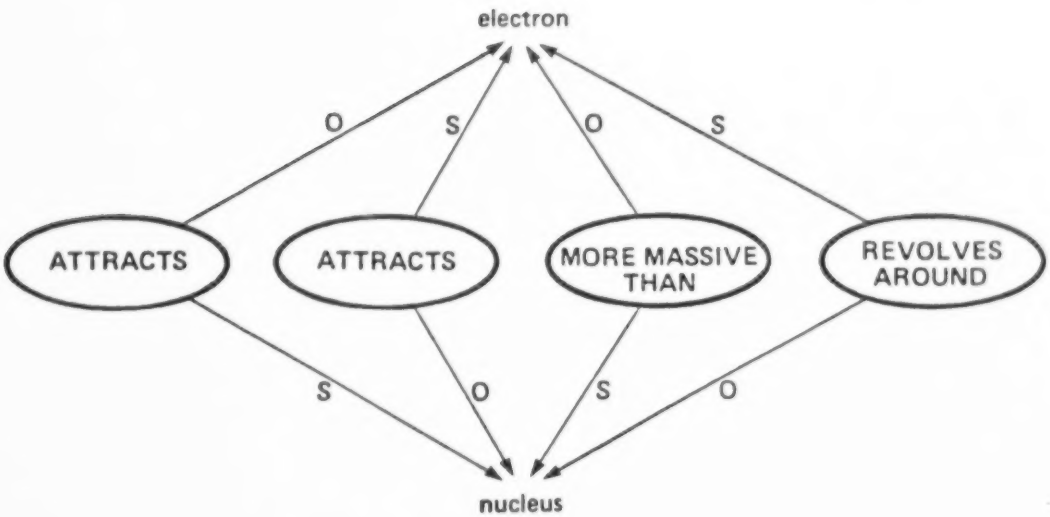
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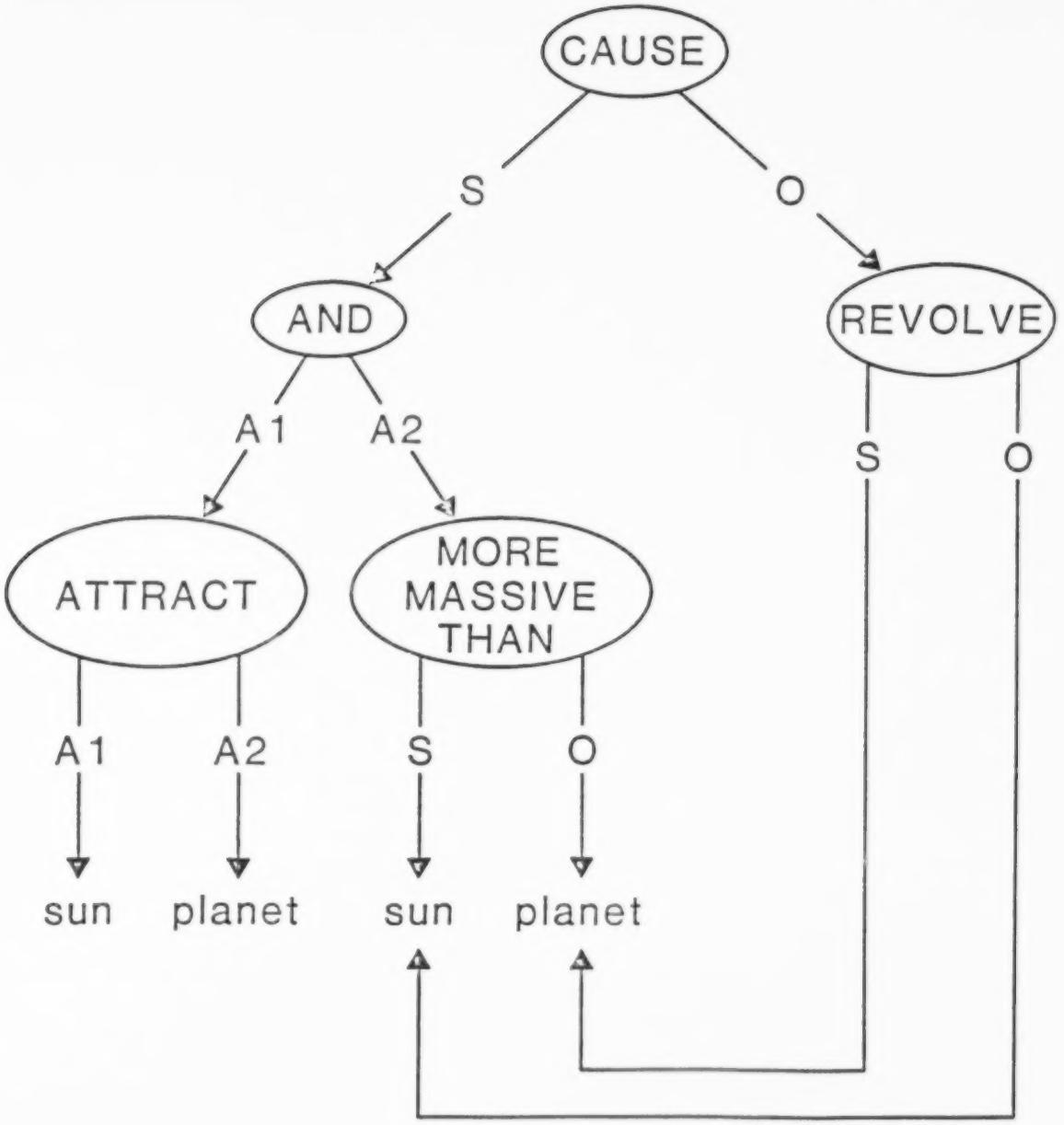
Systematic Partial Representation of Solar System



Non-Systematic Partial Representation of Solar System